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A method for fully automatic operation of domestic heating

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ABSTRACT

Complex, inconvenient and badly arranged push buttons and menus on domestic heating controls often cause users to enter unsuitable settings that result in impaired comfort and poor operating efficiency. This paper proposes a novel approach to the human interface of home heating systems that greatly simplifies the input required from the user. Time settings are derived automatically from electricity consumption and hot water use, also a temperature set point is provided that adapts to user activity levels and external temperature. Practical results from a prototype control system incorporating these methods are reported, showing useful energy savings. It is argued that this increased automation of control allows the benefits of low carbon technologies such as micro-combined heat and power, and solar hot water heating, to be fully exploited.

1. Introduction

Many homes in the UK and elsewhere in Europe employ a boiler fired by natural gas which heats water, for circulation through room radiators to provide space heating, and for domestic hot water. Usually such boilers are controlled by a programmer which can be set to determine the periods during which there is a requirement for space heating, and separately, where there is a storage cylinder present, for hot water. The operating temperature of space heating is usually controlled by a single thermostat, ideally in a central location, though temperature may be regulated in individual rooms if thermostatic radiator valves are fitted. Fig. 1 shows a typical programmer, and Fig. 2 a typical thermostat for space heating.

On the controller shown in Fig. 1, the nine buttons and three sliders that need to be configured to set heating times for space heating and hot water are quite typical in terms of the complexity they present to the user, requiring a total of 28 steps to enter heating times, which are identical for each day of the week. Clearly, performance of this sequence is likely to be challenging to people for a variety of reasons and failure will result in heating times that do not match their needs or in recourse to manual operation of the heating on/off function. Manual switching is likely to result in significant energy wastage through heating being left on when not needed. Thermostats of the form shown in Fig. 2 are relatively straightforward to operate, but they are often installed in inconvenient locations making precise temperature setting difficult, and there is no provision to vary the temperature depending on the occupancy schedules.

As well as anecdotal evidence, there is a substantial body of research showing that people have difficulty with these devices. One study [1] has investigated the effectiveness of improvements to insulation and heating systems implemented under a large scale UK Government programme to address fuel poverty known as Warm Front. It found that 25% of the homes surveyed are persistently cold despite the improvements, and reports (sic):

> "However, a major residual problem was controlling the central-heating system. A third of all respondents over 60 reported difficulty with programmers, with a majority of these saying they were too complicated; "*I don't understand it*," "*I'm not very technical – unsure what to do.*" There were three types of response; first leaving the system as originally set, "*I never touch the controls*;" second, asking friends, family members or neighbours to adjust the setting; third, resorting to manual settings, "*My husband switches it on when he gets up*" However, in [all] these cases, such coping strategies were evidently not successful in securing warm homes."

This is an important finding since the temperature thresholds used by this study to define a cold household were those below which there is increased risk of circulatory and respiratory disease (mean temperatures during winter in living rooms below 18 °C or 16 °C in bedrooms). Another example is a Swedish survey of behaviour with respect to energy use in 600 households [2], which found that 38% of households where the heating temperature could be lowered overnight did not do so, and that "more user friendly technology for adjusting indoor temperatures was a

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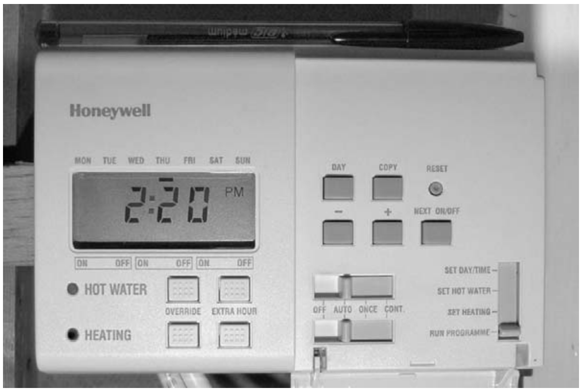

Fig. 1. Programmer for heating times.

Fig. 2. Room temperature thermostat.

commonly proposed policy measure among those who did not currently lower their indoor temperatures". A similar survey comparing behaviour in Norway and Japan found that less than half of the Norwegian households reduced space heating temperatures overnight and 28% did not even reduce them for vacations [3].

More generally, in a recent comprehensive survey of heating control usage in Belgian homes, Peeters et al. [4] observed that despite the trend towards more energy efficient appliances they were not being use effectively because factors such as boiler settings and thermostat programming were quite arbitrary, and were rarely adjusted to suit the specific circumstances of the household. They concluded that "the focus should be on a carefully designed heating system, which is able to adapt itself to a changing demand".

There is therefore a clear need for a form of central heating control that is very simple to use, and preferably provides an acceptable level of comfort and economy without any user intervention at all. This paper describes an approach to realisation of a control system that satisfies these requirements, and reports on initial results from evaluation of a prototype.

2. Concept

2.1. Recognition of occupancy

In order to fully automate the timed control of space heating it is necessary to distinguish as a minimum between three states:

1. The occupants of the home are asleep, so require space heating between 16 and 18 °C.
2. The occupants are awake and active, so require space heating between 19 and 23 °C.
3. The home is temporarily unoccupied, so room temperature can be allowed to fall to a temperature which allows the occupied temperature to be recovered quickly and avoids dampness—around 12–14 °C is suitable for the UK.

These states can potentially be recognised from the electrical load of the house—a typical electrical load pattern over 24 h is shown in Fig. 3. It can be seen that the kettle went on at 7:40 a.m., the house was unoccupied from about 10:00 a.m. to 8:00 p.m., and the occupants went to bed about 11:00 p.m. Between the intervals when the occupants are active and lighting and appliances are operating, the load falls back to that arising just from the fridge and freezer.

Hot water use can also be recognised and quantified to allow water heating to be scheduled, and provides a good indication of occupancy state augmenting that obtained from electrical load. A common practice in the UK and elsewhere is to store hot water in an insulated tank of about 100 l. By equipping the hot water tank with an additional temperature sensor as well as that normally employed for thermostatic control of heat input, information on hot water use can be collected. The additional sensor is placed near the base of the tank. Fig. 4 illustrates a typical pattern of temperatures from these sensors, on a day when the heat source was scheduled to bring the tank up to temperature at 7 p.m. It can be seen that when hot water is drawn off, the temperature at the base of the tank falls sharply as cold water is drawn in. This event alone is sufficient to signal hot water use and occupancy for the purpose of scheduling heat demand. Once draw-off has ceased the tank base temperature rises as the turbulence of the incoming water dissipates and the normal temperature stratification of the tank is recovered. Depending on the volume of water drawn off, there will also be a temperature fall at the top of the tank, although this drop is small until the volume of hot water in the upper part of the tank from the previous heating cycle is consumed.

2.2. Automation of time settings

Since it takes time to heat a dwelling up to a comfortable temperature, and to provide a store of hot water, it is necessary to predict the heating needs of occupants as well as detect them in real time. The proposed control system senses the electrical load and hot water usage to identify and predict which of the three occupant states should apply. To distinguish between "occupants asleep" and "occupants absent" it is necessary to have prior knowledge that they usually go to sleep between late evening and early morning following a period of high electrical load. This information is obtained by a once-only selection from a shortlist, performed by (or for) the user, of a lifestyle model that is recognisable as the nearest to their behaviour pattern. Table 1 lists a minimum set of lifestyle options which will probably be extended in product development. It is envisaged that the option number is entered into the control unit using a thumbwheel switch or similar mechanism.

The identification of occupant state from the electrical load is performed using Bayes' theorem:

$$P(A_1|S) = \frac{P(S|A_1)P(A_1)}{P(S|A_1)P(A_1) + P(S|A_0)P(A_0)} \tag{1}$$

where:

$P(A_1|S)$ is the probability that one or more of the occupants is present and active (A_1), given that the electrical load sensor has

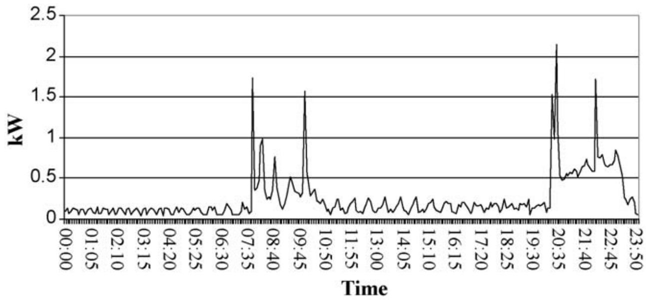

Fig. 3. Example electrical load of home over 24 h.

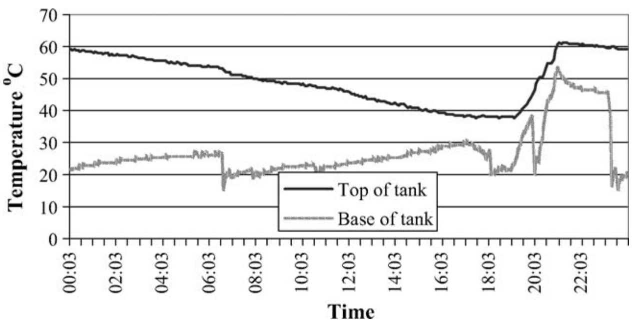

Fig. 4. Hot water tank temperatures.

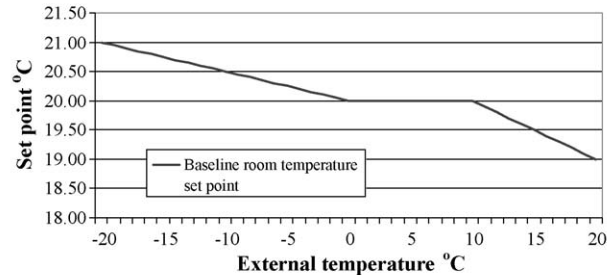

Fig. 5. Adjustment of room temperature set point in response to outside temperature.

given a positive indication (S). This is the posterior probability—if it exceeds a threshold the active state is identified.

$P(S|A_1)$ is the probability that the electrical load sensor will give a positive indication S, if the occupants are active (A_1). This is the likelihood of the sensor—a range of probabilities is assigned dependent on the level of electrical load.

$P(A_1)$ is the probability that the occupants are present and active. This is the prior probability—initial values are provided for each time of day and day of week dependent on the lifestyle option selected. Its inverse is the probability $P(A_0) = 1 - P(A_1)$ that the occupants are not active or absent.

$P(S|A_0)$ is the probability that the electrical load sensor will give a positive indication even when the occupants are not active or absent, i.e., a false indication.

A mean is taken of the posterior probability from Eq. (1) for each time of day with the values for that time from seven previous days to give a prior probability for future use. Since some form of weekly pattern can expected in most lifestyles Mondays are averaged with previous Mondays, Tuesdays with Tuesdays, and so on. The prior probability therefore evolves to reflect the actual behaviour pattern, and time settings in advance for each day can be taken from threshold values of prior probability. This method is also used for hot water timing where necessary, based on actual hot water usage patterns.

2.3. Automation of thermostat setting

The established guidance for indoor temperatures is ISO 7730 [5] which provides an equation relating occupant comfort, as expressed by the Predicted Mean Vote (PMV), to air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing insulation. It would be a simple matter to take a single operating temperature from ISO 7730 that should give a reasonable PMV in many circumstances, as is frequently done for commercial buildings. However, comfort will be improved if the system adapts the temperature automatically where there is information relating to one of the PMV input variables. This is available for lifestyle Option 1, for which it is a reasonable assumption that the occupants will have a metabolic rate in the morning when getting up and dressing that is between 50% and 100% greater than that when resting late in the evening. So for Option 1 the temperature setting is increased during the afternoon and early evening by 2 °C.

There is also research evidence that PMV is dependent on outdoor temperature T_{out}. Humphreys and Nicol [6] have shown that ISO 7730 overestimates the perception of warmth at higher and lower outdoor temperatures, and derive a correction proportional to T_{out}^2. Their finding is that a monthly mean temperature is a preferred metric for T_{out} rather than a value which reflects short term variations. They have also investigated the perception of comfort in buildings which are "free running", i.e., have no systematic heating or cooling [7], and derived an equation for comfort temperature T_c:

$$T_c = 13.5 + 0.54T_{out} \quad \text{for } T_{out} > 10\,^{\circ}\mathrm{C} \tag{2}$$

The homes that are expected to use this control system are likely to be capable of "free running" when $T_{out} > 15\,^{\circ}$C because they are naturally ventilated, and solar gain and heat from electrical appliances will provide an acceptable internal temperature. Temperature tolerance is also increased by the "adaptive opportunity" identified by Baker and Standeven [8] which is normally available in the home, i.e., the ability to change clothing, open windows, and adjust the heating if necessary. So this control system increases the temperature set point for T_{out} below 0 °C using a linear approximation to the findings by Humphreys and Nicol, and reduces it above 10 °C to promote transition to the "free running" regime and improve efficiency. Fig. 5 shows the resulting dependency of baseline room temperature set point on external temperature. This baseline is subject to the metabolic rate adjustment which is applied symmetrically where it is justified by the lifestyle, so that a reduction in temperature in the morning is balanced by an increase in the evening.

Table 1
Lifestyle options for user selection to provide prior probabilities.

Option no.	Lifestyle option	Chosen by
1	I/We are out of the home weekdays, otherwise at home.	People with "office hours" jobs, families with children at school.
2	I/We are at home most of the time.	Retired people, home workers, invalids, families with young children.
3	I/We do not have a regular time to be at work, asleep or out of the home.	Students, shift workers.

To achieve a similar level of automation for water heating, it is necessary to know not only when hot water is used, but how much. By comparing the temperature of the tank base sensor before and after a draw-off event, the proportion of the tank volume that was drawn off can be estimated, and also the proportion of the volume that remains that is within the useful temperature range. To do this the control system models the contents of the tank as comprising an upper volume V_t above the heating coil or element that is all at the temperature T_t indicated by the upper sensor, and a lower volume V_b that is linearly stratified in temperature between that of the upper volume and that (T_f) of the cold feed water. V_t is assumed (from the standardised dimensions of UK hot water tanks) to be 66% of the total volume where the water is heated by the heat exchanger coil, and 50% for the electrical immersion heater. A draw-off volume V_d can then be estimated by the change in temperature of the lower sensor ΔT_b it causes. The lowest temperature seen immediately after draw-off is taken as T_f (for example that seen at 06:30 in Fig. 4) while ΔT_b is measured using the stabilised T_b (as seen at 07:30 in Fig. 4). V_d is then taken as:

$$V_d = V_b \Delta T_b / (T_t - T_f) \quad (3)$$

By integrating these values of V_d from the time immediately after full heating of the tank has been achieved (21:00 in Fig. 4) the progressive consumption of hot water can be monitored. The method is not very accurate, but experimental results indicate that it is fit for the purpose of identifying the relative volumes of each draw-off event allowing heating to be scheduled at the optimum time.

3. Results

3.1. Prototype system

A prototype domestic energy management system based on this concept has been installed in a UK home. Implementation is in the form of a Visual Basic application which is interfaced to temperature and electrical power sensors, and heating control effectors, using an instrumentation controller. Fig. 6 shows the user interface. The "More Heat" button has the effect of bringing heating into operation if it is not timed to be on; if heating is on and at set point temperature then the set point is increased by 0.2 °C for the next 2 h. The "Less Heat" button has an inverse function. These adjustments are memorised, and apply in addition to the automatic variations mentioned above, so that over time a set point that varies during the day to suit the occupants is created.

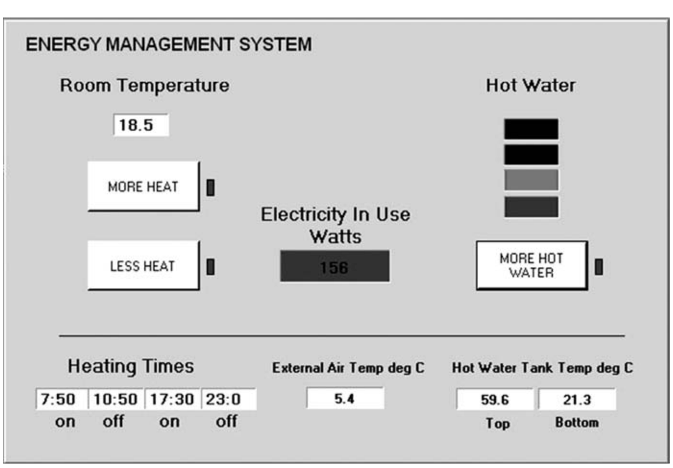

Fig. 6. User interface of prototype control system.

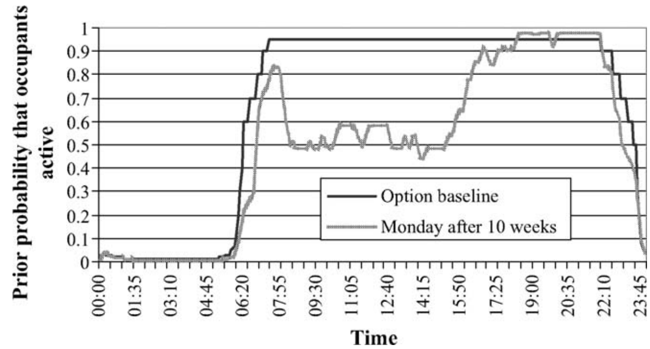

Fig. 7. Convergence of prior probability on actual occupant behaviour.

The colour background to the measurement of electrical load changes to redder colours as the load increases, encouraging economical behaviour, which also makes the recognition of occupancy state more reliable.

Fig. 7 shows how the prior probability evolves in use to capture consistent occupant behaviour. On start up Option 2 was selected which provides an initial set of prior probabilities that are constant between 08:00 and 22:00. However the occupants were regularly out of the house during daytime on Mondays resulting in development of the prior probabilities shown after 10 weeks operation. The heating times are derived at $P(A_1) = 0.6$ giving 06:40-08:10 and 15:35-22:45.

Practical operation of an automatically varying room temperature set point is illustrated in Fig. 8, for the same day as shown in Fig. 7. The three levels reflecting the three identified occupant states are clear—the set point rises prior to the required heating times to allow warming up time. The small rises in set point during the afternoon and evening were entered manually using the "More Heat" button. It is unlikely that these occupants would have turned off their heating during the day on Mondays if they were using a conventional programmer such as that shown in Fig. 1, because their normal lifestyle pattern is to be mainly at home in accordance with their selection of Option 2. The dip in room temperature during the unoccupied state shows that an energy saving has been achieved, although in the case of this prototype installation it is quite small (2.9 kWh) because of the high aggregate thermal capacity (16 kWh/°C) of the house.

Detection and scheduling of hot water use is illustrated in Fig. 9. The downward steps in the plot of heated volume at 07:00, 15:00, and 23:00 show where hot water use has been recognised and quantified by the system. The upward step at 22:30 reflects the heating of the tank, as can also be seen in the temperature spike. Tank heating has been timed by the system to take place shortly before the major hot water use of the day when the occupants take a shower.

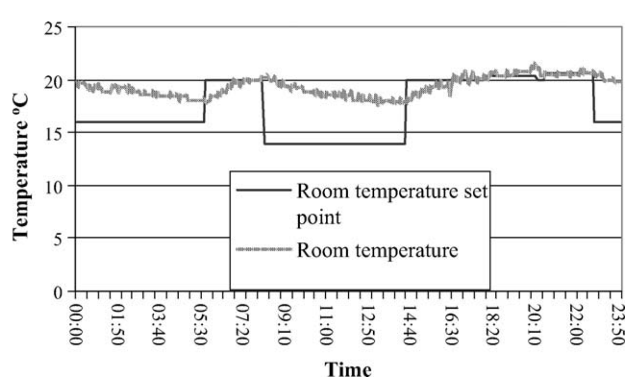

Fig. 8. Variation of room temperature set point, and resulting room temperature.

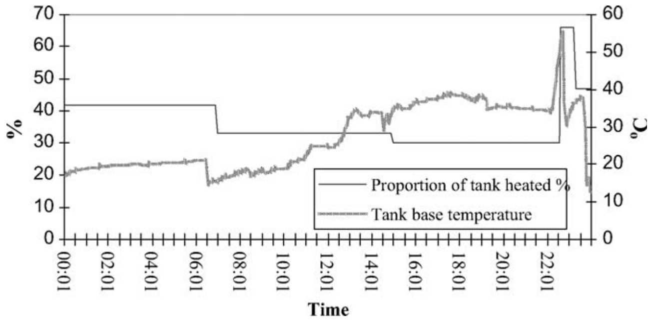

Fig. 9. Hot water tank usage measurement.

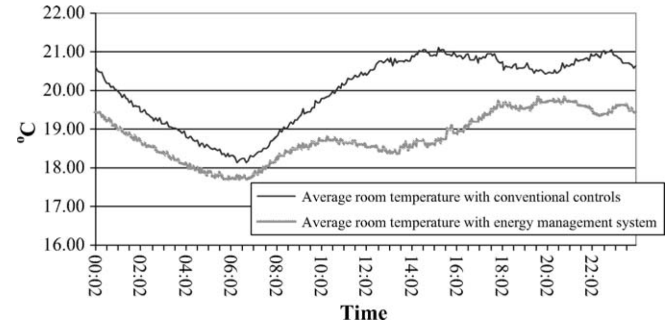

Fig. 10. Average room temperatures before and after introduction of prototype.

3.2. Energy savings

To assess the practical benefits of the prototype a detailed comparative analysis of heating performance in the test household was undertaken during April 2008. The traditional devices shown in Figs. 1 and 2 provided control of heating for 2 weeks (the "before" period), then the prototype system was given control for 2 weeks (the "after" period). During the "before" period, the heating programmer was set for heating to be "on" between 06:45 and 23:00 every day, and the room temperature thermostat was set to 19.5 °C. Hot water heating was provided by a control arrangement known in the UK plumbing trade as a "W" plan. This requires that the hot water temperature is above the thermostat set point before space heating commences, so hot water is heated first if necessary when there is a demand for space heating. It also has the effect that the hot water cylinder is used as a sink for the residual heat that is drawn from the gas boiler when space heating is ceased by continued operation of the radiator circulation pump for about 10 min. During the "after" period the prototype system operated as described above, and also included a more efficient arrangement for residual heat from the boiler by ensuring it was always directed for space heating.

When household energy flows were compared for the "before" and "after" periods, and adjustments made for differences in solar gain, external temperatures, and electrical load, the energy savings attributable to the energy management system could be identified as shown in Table 2.

Average room temperatures for the "before" and "after" periods are shown in Fig. 10. The average room temperatures above the nominal set point during the "before" period arose from a combination of factors—the room thermostat had a wide and fluctuating hysteresis of about +1 °C, there were some days where solar gain was significant, and there was some use of an auxiliary heating source by the occupants. The lower temperatures during the "after" period arise from precise control of the room temperature set point, and a reduction in the time interval when a comfortable room temperature was required. This time interval was reduced from the fixed 16.75 h/day "before" to an average of 11.7 h/day "after", with a range from 5 to 15.5 h reflecting accurately the variable occupancy during the two weeks "after".

The improvement in boiler efficiency arose as a consequence of the other two sources of energy savings. The improved use of residual heat from the boiler and lower average room temperatures resulted in lower average temperatures for the water circulating through the radiator system and the heat exchanger within the boiler.

Table 2
Energy savings achieved by prototype energy management system.

Source of energy saving	Reduction in gas consumed by boiler (kWh/day)	As % of daily "before" consumption
Lower average room temperature	12.8	9.4
Capture of heat from pump overrun	4.2	3.1
Increased boiler efficiency	2.2	1.6
Totals	19.2	14.1

4. Discussion

The results obtained in Section 3 are based on relatively limited prototyping. However it is expected that they will be repeatable in a wider range of settings and it is considered that they justify further proof of concept planning at this stage. Clearly the current context of the electricity market and government policy as expressed in the 2007 White Paper [9] should be strongly considered in these plans. The electricity supply industry is working closely with the UK government to promote energy efficiency and one approach that has been closely studied is the exploitation of feedback effects. There is ample research evidence that giving people immediate information on their electricity consumption encourages greater energy efficiency (see Darby [10] for a comprehensive review). One of the key interventions based primarily on feedback will be the introduction of smart meters, which are expected to deliver very significant energy savings (from 4% to 12% according to [11], for example). The novel approach proposed in this paper has excellent synergy with the feedback concept and integration with smart metering should give additional benefits. The prototype user interface shown in Fig. 6 could be installed in a convenient location, e.g., above a kitchen worktop, using wireless or mains-borne signaling of electrical load from the meter to provide the required feedback. This system would enhance the benefits derived from the user's response to this feedback, by delivering greater energy efficiency through more precise timing of heating and lower thermostat settings that are nevertheless still within the parameters of user acceptability.

The automation of control offered by this concept also allows more effective use of low carbon technologies in the home by hiding the complexity arising from their use, such as intermittency, load matching and, where multiple technologies are installed, interactions between them. The evaluation of micro-CHP reported in [12] shows that for electricity generated from this source, accurate heating time settings combined with a rising room temperature set point improve the proportion consumed within the home, rather than exported to the grid, by about 20%. This is highly beneficial as local consumption of CHP generated electricity improves the financial value of micro-CHP to the user, and reduces losses in the electricity distribution network.

Another example is provided by the use of solar hot water heating in a climate such as the UK with intermittent insolation. In order to meet domestic hot water heating demand it is essential that solar heating can be augmented as necessary with an auxiliary source of heat (such as an electrical immersion heater) to guarantee an adequate temperature. The timing of the auxiliary source is however quite critical and variable—if for example the auxiliary heating is applied too early in the day there will be less opportunity for a contribution from solar heating. Clearly, the novel methods described in Section 2 would address this problem effectively, by allowing the system to learn the hot water usage patterns of the occupants and by optimally controlling the auxiliary heat source, taking current day length into account.

5. Conclusions

The initial results from a heating-focussed prototype of a novel self-configuring domestic energy management system have been presented. The deficiencies of existing controls and their adverse effects on energy efficiency and, indirectly, on the health of users have been identified. The results strongly suggest that it should be possible to develop a marketable product, which would have great potential for mitigating these effects. Additional proof of concept has been demonstrated in a preliminary design for a simplified user interface that would permit integration with smart meter technology to provide additional leverage to the energy saving and financial benefit from its expected wide scale deployment. The concept can be readily generalised and developed for wider application to systems incorporating different low carbon technologies such as heat pumps, micro-CHP, and solar hot water heating, whether used singly or in combination. By simplifying or removing entirely the management interventions that would otherwise be required from the users, this would represent a very significant step towards the more general acceptance and uptake of these technologies that is considered essential if carbon reduction targets are to be met.

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